

# The Astrobiology of the **Subsurface**

*Caves & Rock Fracture Habitats on Earth, Mars, & Beyond*



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Art: Adam Hetmansky

*“What’s a Nice Girl Like You Doing in a Place Like... THAT?”*



Image courtesy of T. Kieft

*Unparalleled opportunity to look glamorous at all times...*





# NASA Astrobiology Institute

## LIFE IN THE UNIVERSE


A Division of the NASA  
Astrobiology Program



Origin and  
Nature of Life,  
Co-evolution  
with Planet Earth



*Mars: NASA's Journey to Mars*  
Habitability  
of Early Mars



Icy Worlds:  
Habitability  
and Life  
Detection



Exoplanet  
Biosignatures

NAI: US & Global Community



# NASA Science Mission Directorate

## Planetary Science Division

### Astrobiology Program

Habitable  
Worlds

PICASSO

**PSTAR:**  
*Planetary Science &  
Technology in  
Analogue Research*

Exo-Evo

**NAI**

**NExSS**  
*NASA Exoplanet  
System Science*



# It's good to be the Queen...of NAI!



*It's Good to be the Queen – By Paula Baker*

- Competitively-selected science teams
  - ~320 senior scientists
  - ~280 postdocs and students
  - ~20 US Nat Acad Sci members
- ~600 members
  - ~320 senior scientists
  - ~280 postdocs and students
  - ~20 US Nat Acad Sci members
- ~100 participating institutions
- NAI Central - NASA Ames Research Ctr
- Programmatics— Astrobiology Program at HQ

## Current Lead Institutions

- Massachusetts Institute of Technology
- University of Illinois at Urbana-Champaign
- University of Southern California
- University of Wisconsin
- VPL at University of Washington
- NASA Goddard Space Flight Center
- NASA Ames Research Center
- NASA Jet Propulsion Laboratory
- SETI Institute
- University of Colorado in Boulder
- University of California, Riverside
- University of Montana in Missoula

# Astrobiology JOB 1:

Figuring out possible lifeforms from first principles!



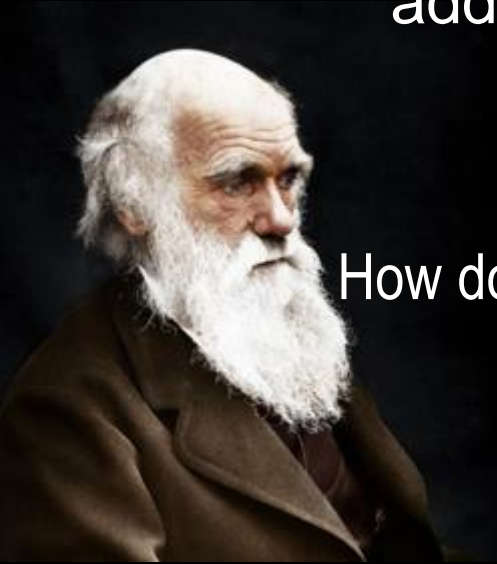
*"Ammonia! Ammonia!"*

Drawing by R. Grossman; © 1962.  
The New Yorker Magazine, Inc.

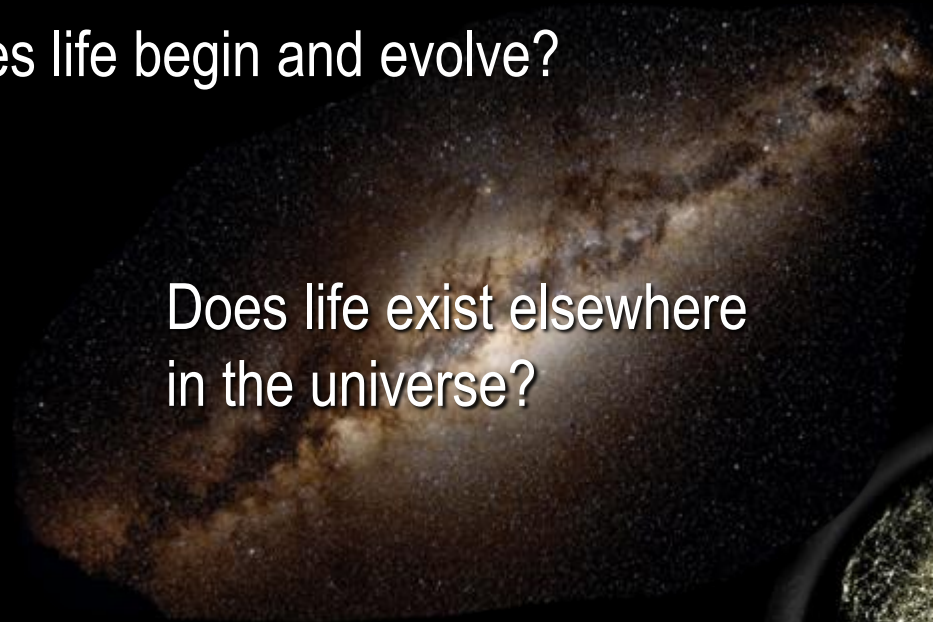


# Astrobiology

addresses three fundamental questions:



How does life begin and evolve?



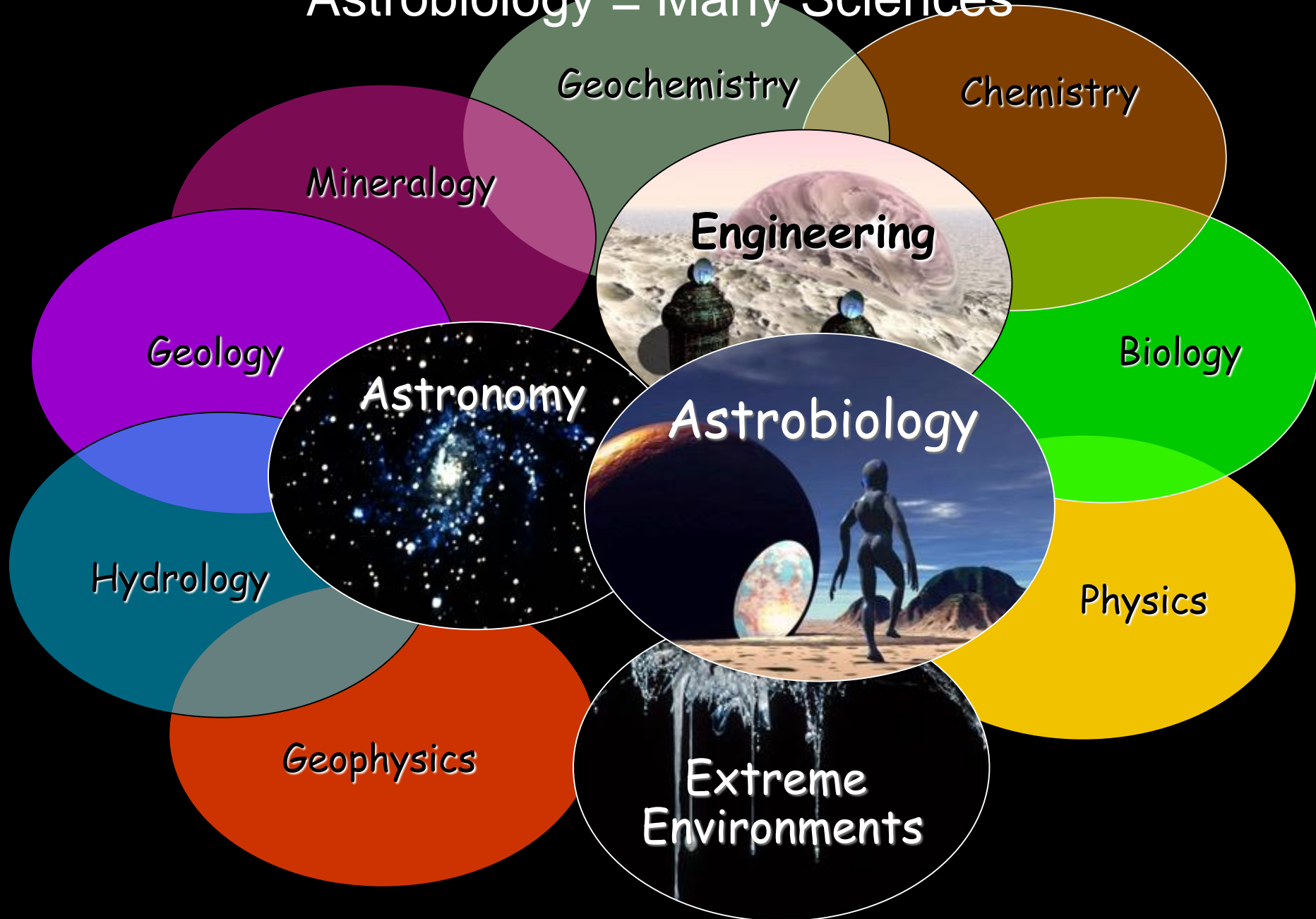
Does life exist elsewhere  
in the universe?

What is the future of life  
on Earth and beyond?

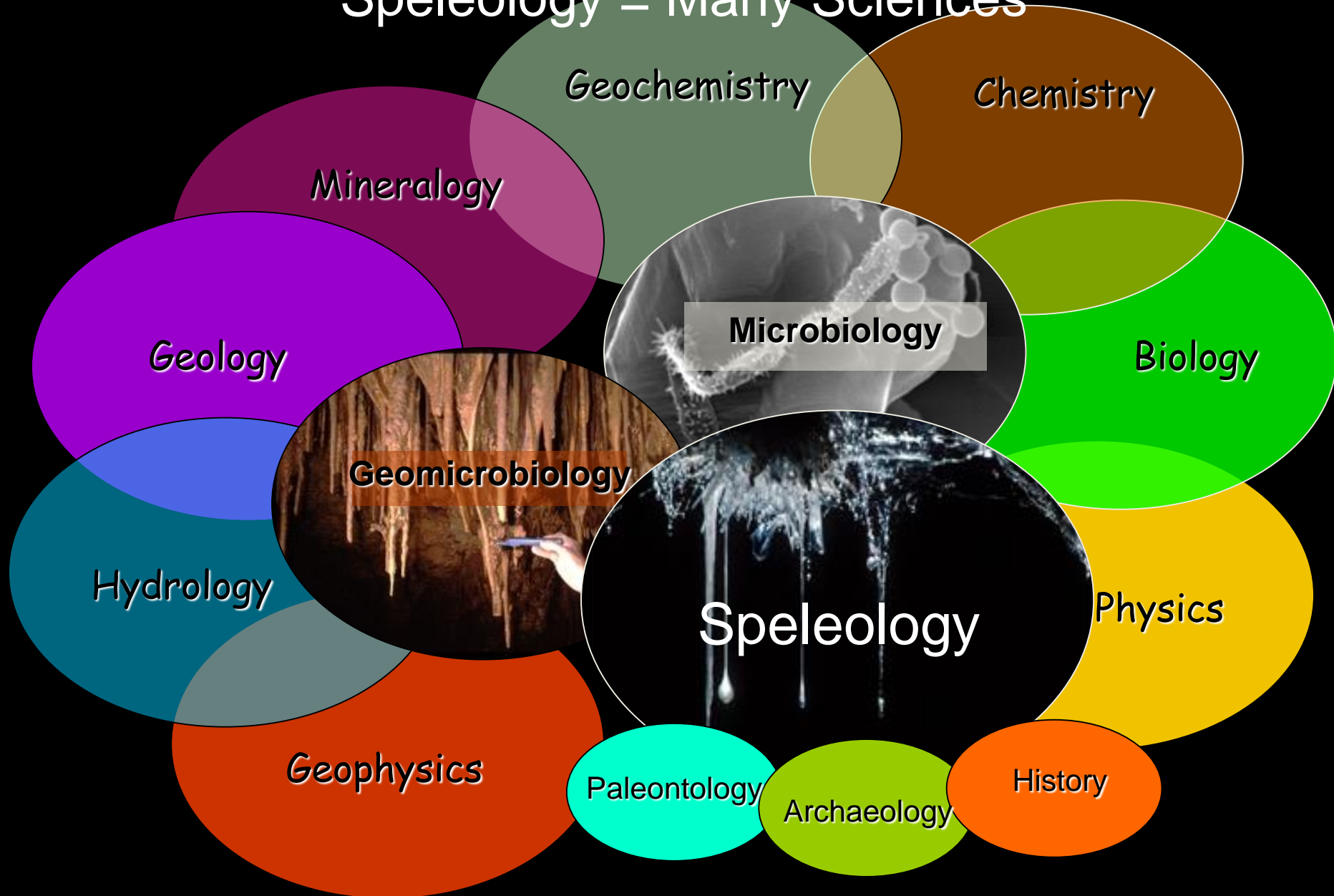




# Astrobiology = Many Sciences



# Speleology = Many Sciences





# Subsurface Rock Habitats

## Rock fracture habitats

- *Water-storing rocks (Aquifers)*
- *Caves*
- *Mines (anthropogenic caves!)*
- *Ocean floor rock fractures*
- *Ocean caves*







Snowy River Passage, Ft. Stanton Cave, NM  
Image by J. Ganter

# The Planet Within

Caves & mines provide a window into a subsurface that is **radically** different from the surface

Rub al Khali (Empty Quarter)  
Saudi Arabia, Oman, Yemen, and United Arab Emirates

*Images courtesy of John Pint*





# Subsurface Environments

- No sunlight (past the twilight zone)
- High humidity
- Temperatures constant
- Low organic nutrients
- Mineral-rich
- Unusual chemical energy sources (e.g.  $\text{H}_2\text{S}$ )
- No surface weather
- Splendid preservation environment!



Entrance Drop  
Lechuguilla Cave, NM  
Photo courtesy of David Jagnow



# What is Geomicrobiology?

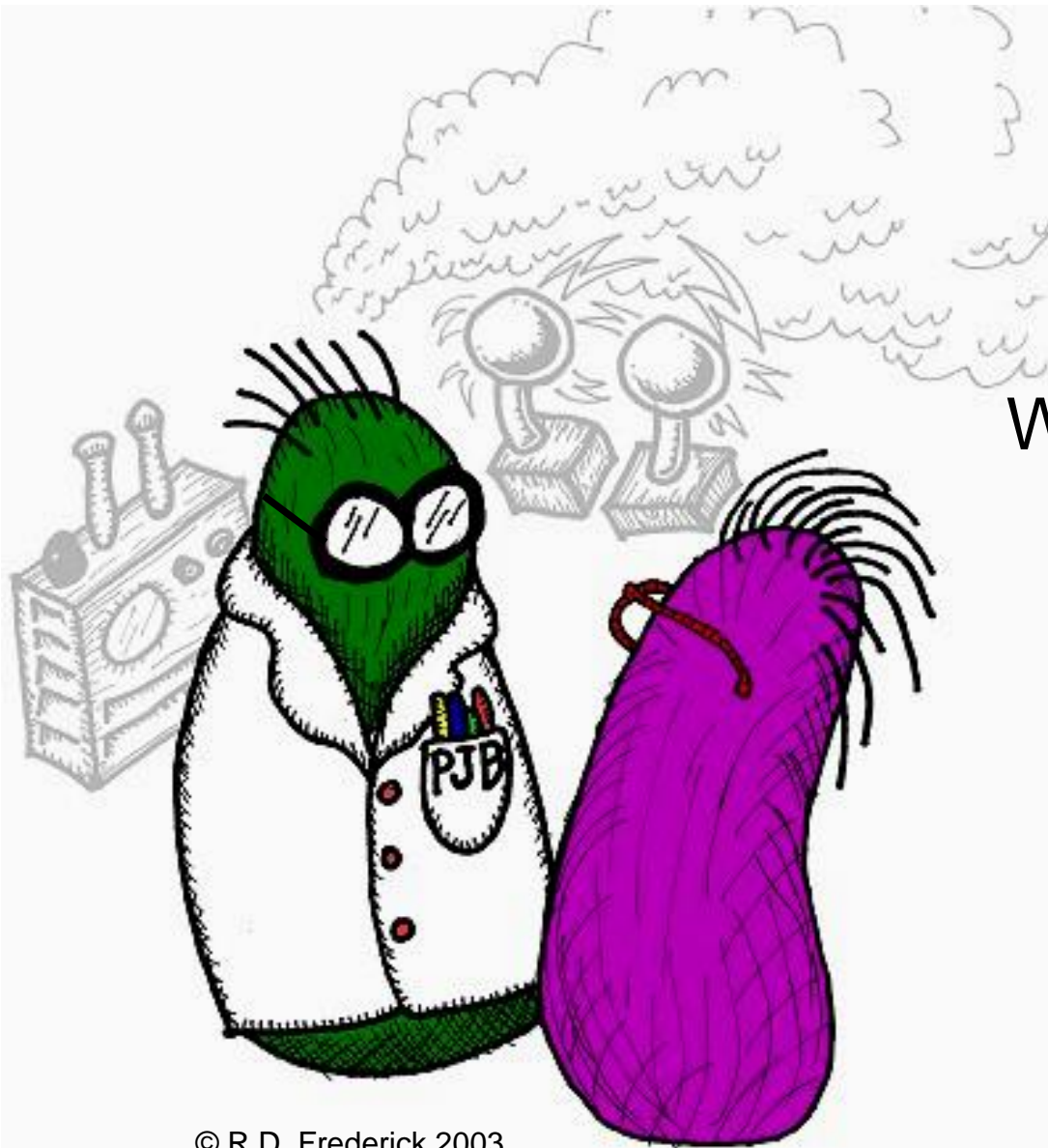
*Microorganism interactions  
with rocks and minerals*

## What do microbes do?

Transform materials

Destroy bedrock

Precipitate biominerals  
**actively** & **passively**



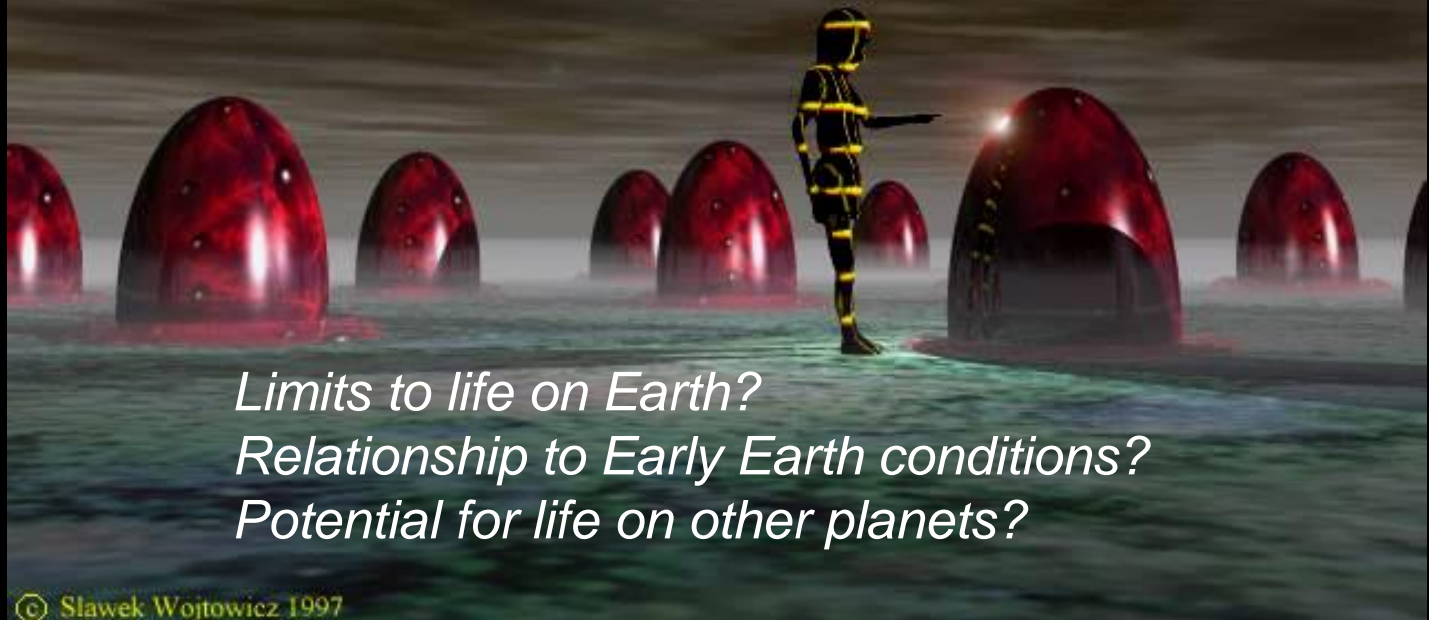
# Significance of Geomicrobiology

- Geological weathering agents
- Economic minerals
- Unusual minerals
- Low temperature enzymes
- Pharmaceutical potential
- Unknown organisms & biochemistry
- Origins of life & early evolution
- **Astrobiology**



...the search for life in the universe...

*Writing the Field Guide to*  
**Unknown Organisms**



*Limits to life on Earth?  
Relationship to Early Earth conditions?  
Potential for life on other planets?*

© Sławek Wojtowicz 1997

By courtesy of the artist



# Extraterrestrial Caves



© 1998 Slawek Wojtowicz

By courtesy of the artist

# What Do We Know About Extraterrestrial Caves?

knowledge



- Lava tube caves on a number of bodies (Moon, Mars, etc.)

- Any planet with a surface will develop cracks
- Cracks provide the foundation for:
  - dissolved caves (e.g. limestone, gypsum, salt)*
  - crust motion (tectonic) caves*
  - cave-formation mechanisms that don't happen on Earth*

- Caves from entirely non-Earth processes?
  - e.g. sublimation of cometary ices or Martian poles?*
  - Titan karst in tholin organic goo?*

speculation



Caves of Europa, P.J. Boston

# We've known about extraterrestrial cave-forming processes since the dawn of the Space Age!

Oberbeck, V.R., Quaide, W.L., & Greeley, R.. 1969.  
On the Origin of Lunar Sinuous Rilles, *Mod. Geol.* 1:75-80,



The Moon - Vallis Schroteri , Aristarchus  
Image, NASA



Hawaii, Open lava channels forming  
Image, USGS



# Extraterrestrial Lavatubes & Pit Caves

All images, NASA

Moon

Mare Tranquilitatus

100 meters

Mare Ingenii

100m

Io

50 km

Mars

Mercury

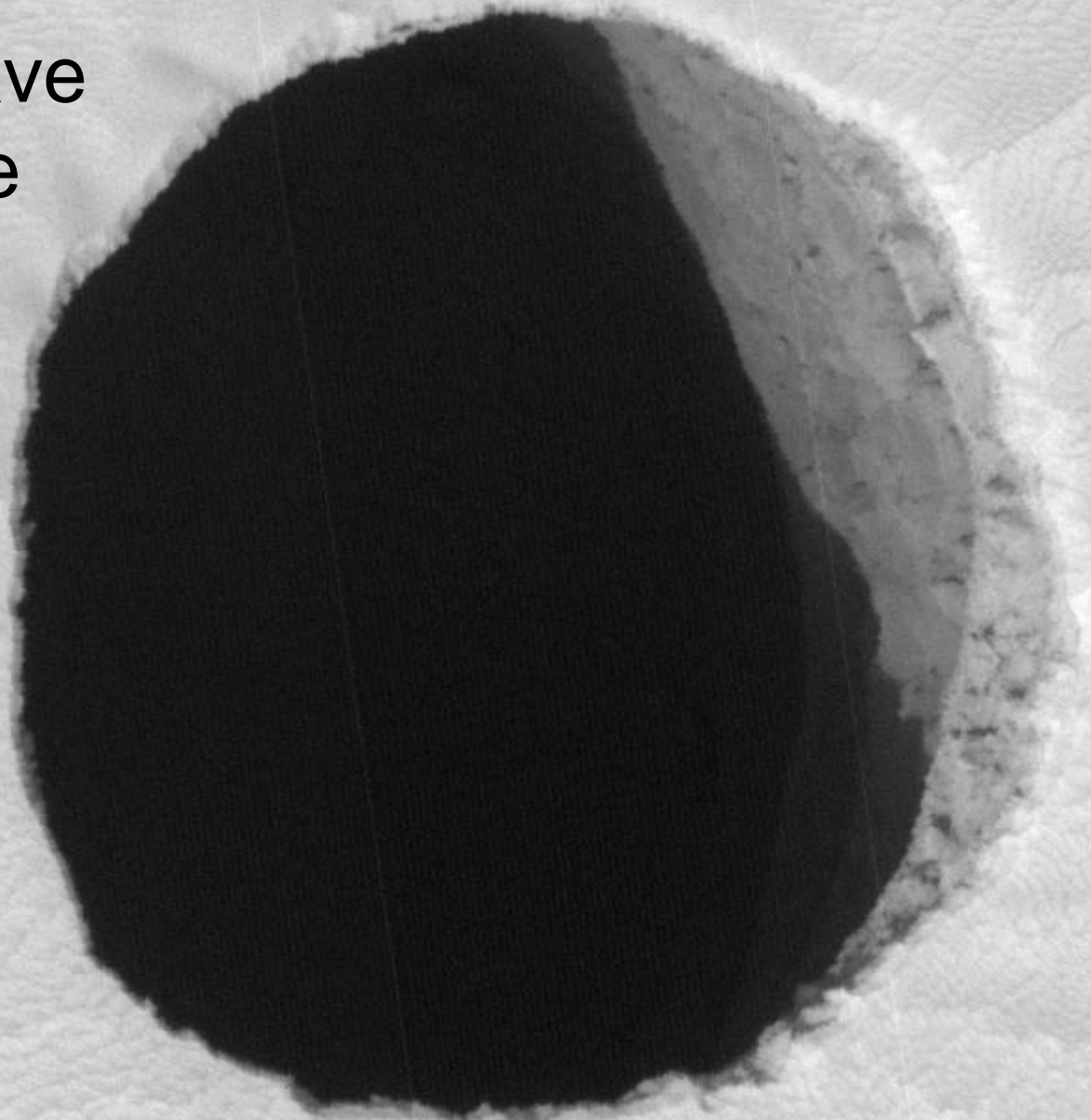
Venus

35 m  
↔

Boston, P.J. 2004. Extraterrestrial Caves. *Encyclopedia of Cave and Karst Science*. Fitzroy-Dearborn Publishers, Ltd., London, UK. Pp. 355-358.

# Martian Cave Entrance

HiRise data  
30 cm resolution  
Hole is 100 m across!

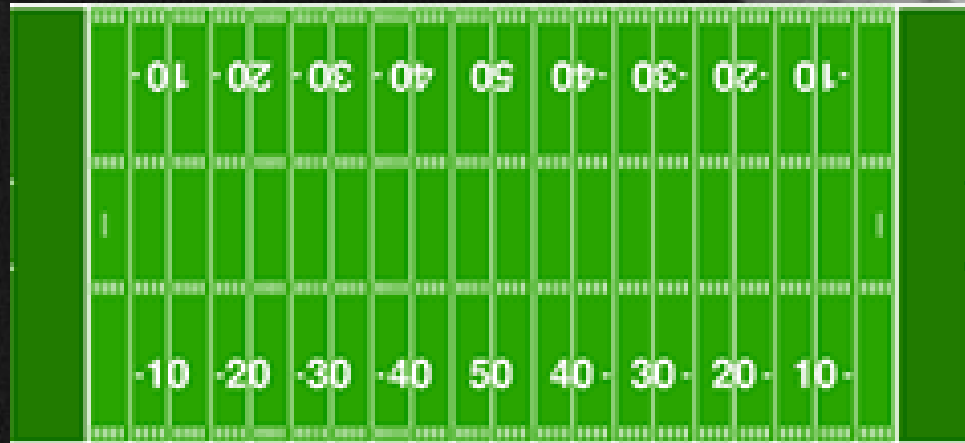




# Martian Cave Entrance

*Compared to an American football field*

HiRise data  
30 cm resolution  
Hole is 100 m across!





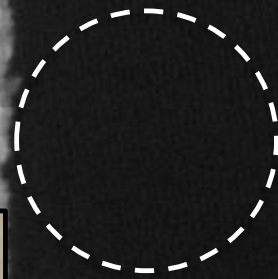
# Martian Cave Entrance

*compared to an American sinkhole!*

West Desert Sinkhole  
Utah



Google Earth



# West Desert Sinkhole, Utah



~22 meters diameter

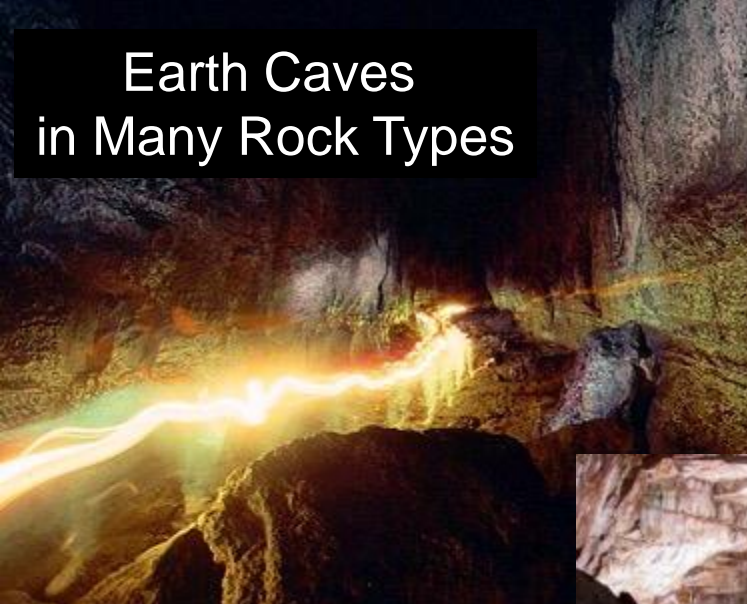




*Santa Cruz Is., Galapagos Is  
~80m diam volcanic collapse feature*



# Earth Caves in Many Rock Types



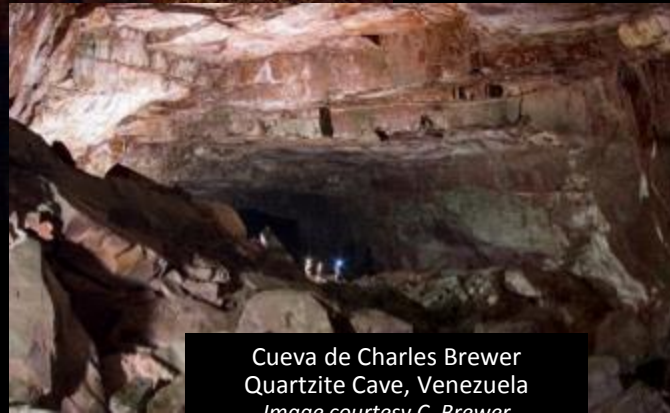
Four Windows Lavatube,  
El Malpais Nat. Monument. Grants, NM  
*Image courtesy of K. Ingham*



Granite spalling caves  
Galicia, Spain



Lechuguilla Cave, Carlsbad, NM  
created by sulfuric acid and limestone  
*Image courtesy D. Bunnell*



Cueva de Charles Brewer  
Quartzite Cave, Venezuela  
*Image courtesy C. Brewer*



Antarctic ice caves, Mt. Erebus  
*Courtesy of A. Curtis*



Caves in Salt  
Atacama Desert, Chile



Submarine caves  
Costa Rica  
*Courtesy of J. Mylroie*



Lilburn Marble Cave, CA



Parks Ranch Gypsum Cave,  
Carlsbad, NM

# Process-based Cave Classification

CAVE TYPE	Dominant Processes	Parent Materials	Earth Examples	Possible Extraterrestrial Variations
<b>Solutional</b>	Dissolving rock by solvent ( <i>With or without chemistry</i> )	Soluble solids plus a solvent	Classic karst, gypsum, halite	Non-water solvents, different thermal regimes
<b>Erosional</b>	Mechanical abrasion via wind, water, grinding, crystal wedging, etc.	Any solid	Sea coast caves, Tafonation, Aeolian rock shelters, etc.	Non-Earth erosional processes, e.g. radiation sputtering, frozen non-water volatile wedging
<b>Tectonic</b>	Fracturing due to internally or externally caused earth movements	Any rocky solid	Seismic caves	Tidal flexure from a massive primary planet or sun, impact fracturing in craters
<b>Suffosional</b>	Cavity construction by the fluid-borne motion of small particles	Unconsolidated sediments	Mud caves, some “thermokarst”	Ground ice sublimation (?) pocking at Mars poles
<b>Phase Transition</b>	Cavity construction by melting, vaporization, or sublimation	Meltable or sublimable materials capable of solidifying at planet-normal temperatures	Lava tube caves, glacières’ caves (i.e. caves in ice as bedrock), “thermokarst”	Perihelionic sublimation of frozen volatiles in comets (Temple), frozen bubbles in non-water ices, non-basalt lavatubes (Io)
<b>Constructional</b>	Negative space left by incremental biological or accretional processes, often around an erodable template	Any solid capable of ordered or non-ordered accretion, or biogenic processing	Coralline algae towers, travertine spring mound caves	Crystallization in non-polar ices leaving voids?

Modified from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst*, J. Gunn, ed.

Titus & Boston, 2012. Interdisciplinary research produces results in the understanding of planetary caves. *EOS Trans.* 93(20):196.

# Process-based Cave Classification of Target Bodies

CAVE TYPE	Dominant Processes	Parent Materials	Earth Examples	WHERE????
<b>Solutional</b>	Dissolving rock by solvent (With or without chemistry)	Soluble solids plus solvent	Classic karst, gypsum, halite	Earth, Titan, Mars
<b>Erosional</b>	Mechanical erosion via wind, water, glacial, crystal wedging, etc.	Any solid	Sea coast caves, glacial erosion, aeolian rock etc.	Earth Mars (aeolian, tafonation) Titan (coastal?) Venus (aeolian?)
<b>Tectonic</b>	Fracturing or external movements	Any solid	Fracture caves	Earth, Europa Ganymede? Titan, Enceladus Mars
<b>Suffosional</b>	Cavity construction by fluid-borne erosion of particles	Any solid capable of eroding	Gravel caves, sinkholes, etc.	Earth Mars (poles, RSL layers?)
<b>Phase Transition</b>	Cavity construction by melting, vaporization, or sublimation	Any solid capable of sublimating at planetary temperatures	Lake tube caves, glacial caves (i.e. caves in ice as bedrock)	Volcanic bodies (Earth, Mars, Venus, Io) Comets
<b>Constructional</b>	Negative space left by incremental biological or accretional processes, often around an erodable template	Any solid capable of ordered or non-ordered accretion, or biogenic processing	Coralline algae towers, travertine spring mound caves	Earth Mars (spring mound cavities)
<b>Compound Mechanisms *</b>	<b>Catastrophic speleogenesis</b>	<b>Rocky soluble solids</b>	<b>Flynn Creek Impact structure**</b>	Earth Mars

Where should we put...

Ceres?  
Vesta?  
Pluto?  
Mercury?  
Uranus' moons?

Modified EVEN MORE from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst*, J. Gunn, ed.

\* Boston et al. 2006. In, *Karst Geomorphology, Hydrology, & Geochemistry* GSA Special Paper 404. Pp. 331-344.

\*\* Milam et al. 2005. Flynn Creek Impact Structure. 69<sup>th</sup> Ann. Meteoritical Soc. Meeting Field Guide.

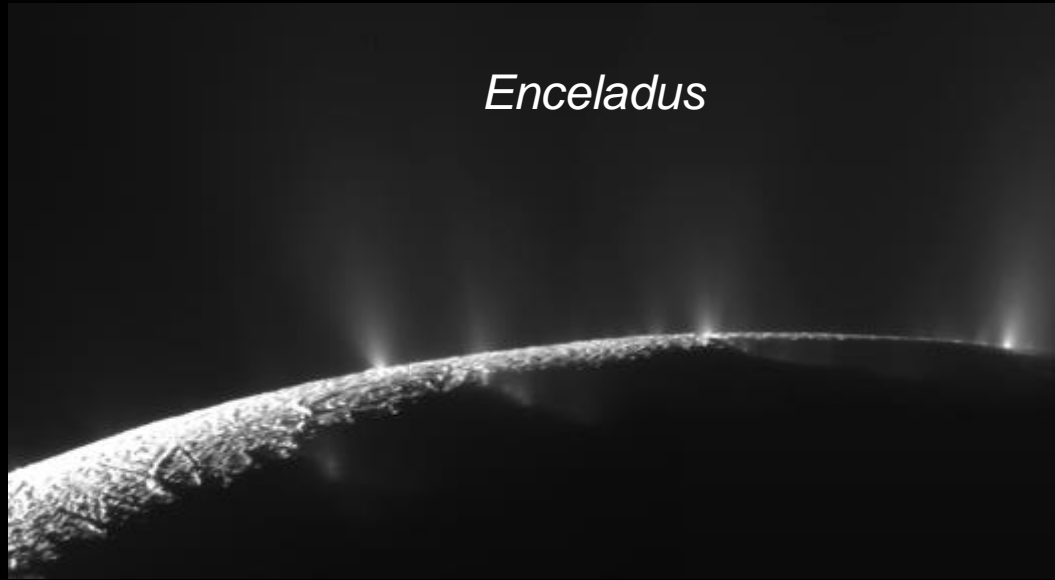


Icy Satellites...not “ocean worlds”, but planet-sized aqueous caves!

*Europa*



*Enceladus*



# Cave Potential on Icy Bodies

✧ *Whole planet/moon*

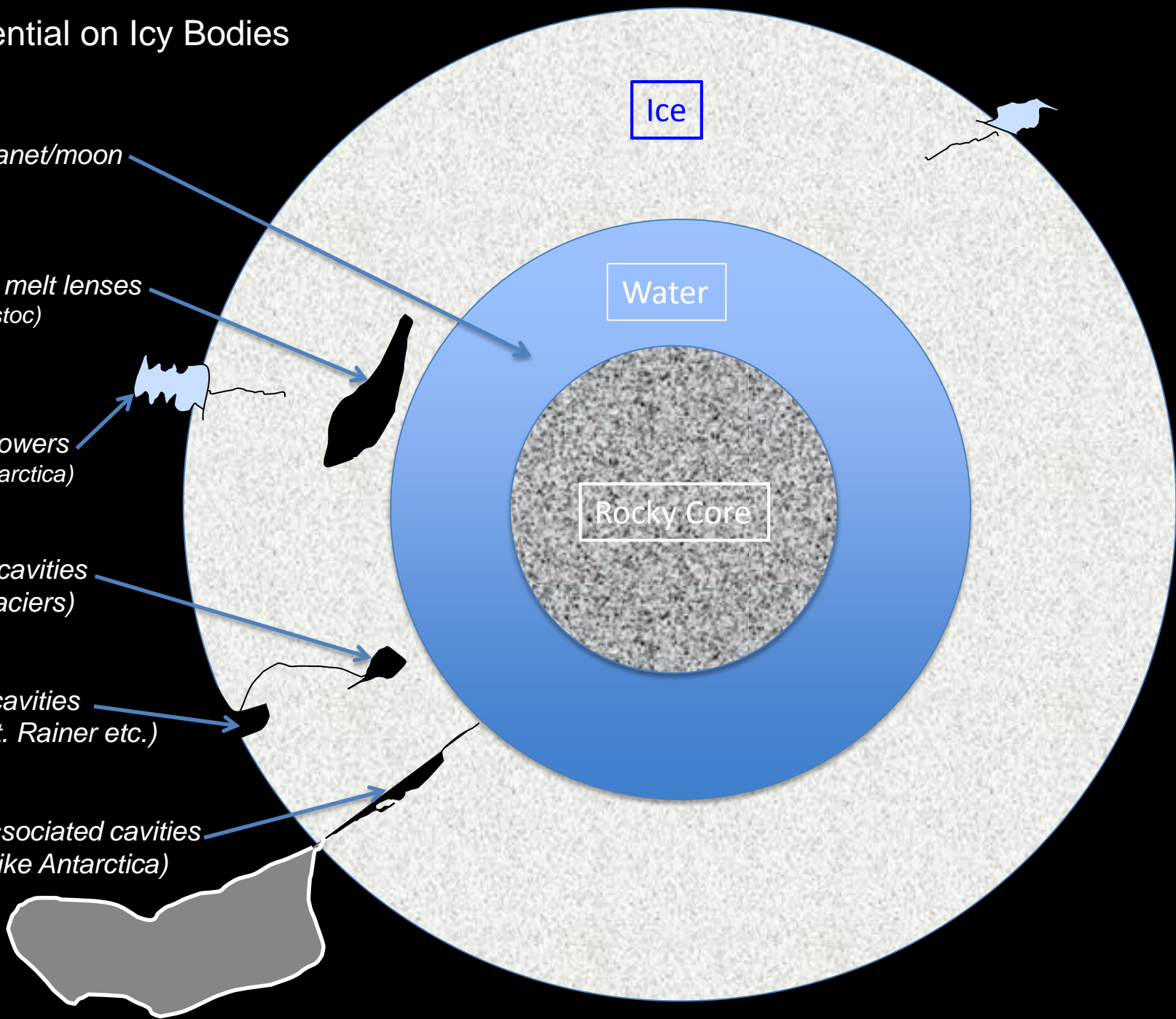
✧ *Pressure melt lenses  
(like Vostoc)*

✧ *Surface towers  
(like Antarctica)*

✧ *Fracture cavities  
(like glaciers)*

✧ *Surface cavities  
(like Mt. Rainer etc.)*

✧ *Plume associated cavities  
(sorta like Antarctica)*



# Ice Towers & Caves on Mt. Erebus, Antarctica & Mt. Rainier, WA

*May be some on Mars, Europa, & Enceladus!*



Courtesy, Aaron Curtis



© Karen Hilton

Historical Photograph



Courtesy, Eddy Cartaya





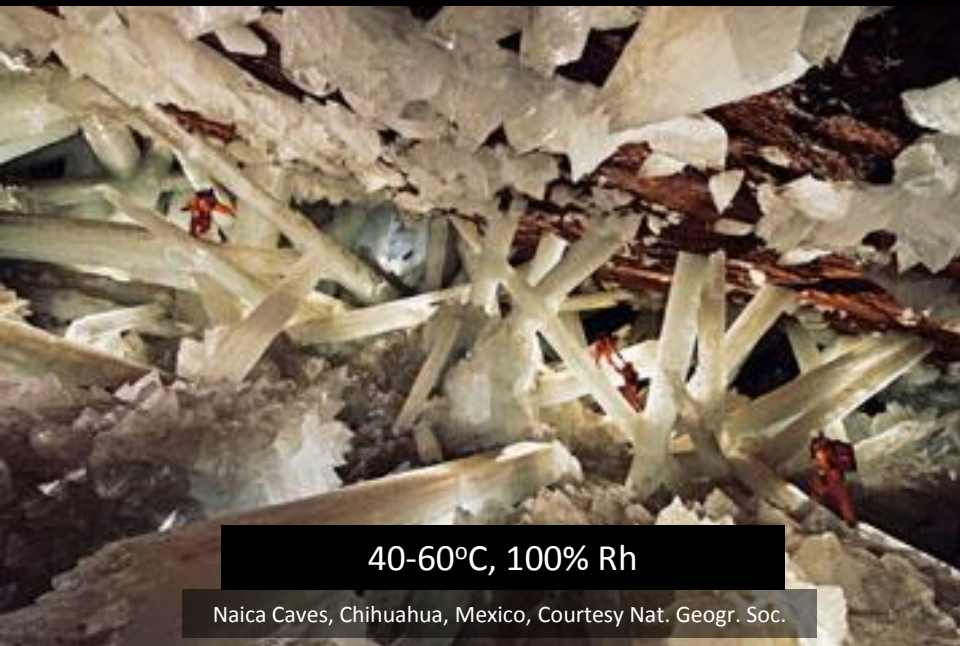
Sulfuric acid ( $\text{pH}=0$ ),  $\text{H}_2\text{S}$ ,  $\text{CO}$ , & other poisonous gases

Cueva de Villa Luz, Tabasco, Mexico, Courtesy Nat. Geogr. Soc.



$-3^\circ\text{C}$ , poisonous  $\text{SO}_2$  & other gases

Fumarolic Ice Caves, Mt. Rainier, WA, Courtesy Eddy Cartaya



$40\text{--}60^\circ\text{C}$ , 100% Rh

Naica Caves, Chihuahua, Mexico, Courtesy Nat. Geogr. Soc.



World's largest cave decoration, 18.5km & going

Snowy River, Ft. Stanton Cave, NM, Image, BLM

# What Kind of Planet Is It?

## **Planet Type 1 Biosphere**

*Sunlight “just right”*

*Green*

*Goosey*

*Gases in non-equilibrium*

*Critical Zone is top-down*

*Photosynthetically driven*

## **Planet Type 2 Biosphere**

*No visible means of support*

*Not green*

*Not goosey*

*Gases in chemical equilibrium*

*Exceptions dependent upon crustal leakiness*

*Critical Zone is bottom-up*

*Chemosynthetically driven*

Well mixed-Critical Zone

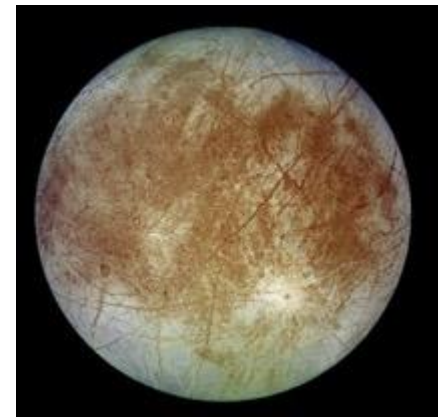


*Earth*

Stratified Critical Zone?



*Mars*

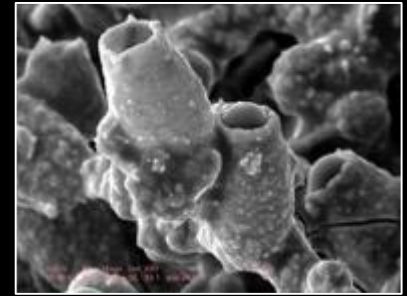


*Europa*

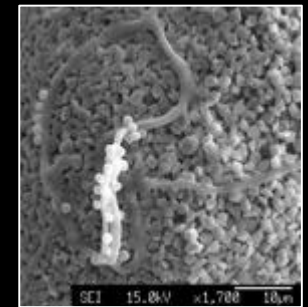
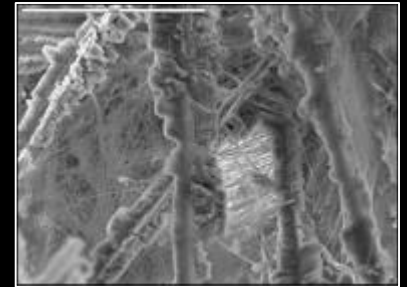


# Biosignature Suites at Many Scales

Red Tulip Microbial Iron Stalagmites,  
Zoloushka Cave, Ukraine



Poofball Sea, Thrush Cave,  
SE Alaska



SEMs by M. Spilde & P. Boston

Boston, P.J. et al 2001. Cave biosignature suites: Microbes, minerals and Mars. *Astrobiology* 1(1):25-55.

Red Tulip Microbial Iron Stalagmites,  
Zoloushka Cave, Ukraine



Poofball Sea, Thrush Cave,  
SE Alaska



snottites!  
*Image courtesy K. Ingham*



Phlegm ball mats  
*Image courtesy K. Ingham*



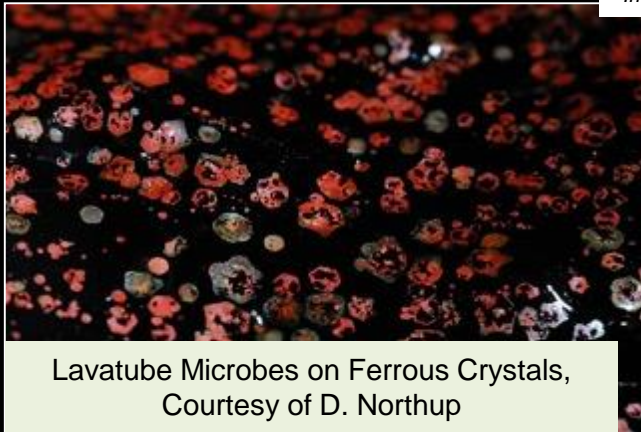
Manganese Microbe Stalagmite on  
Miner's Jacket, Soudan Mine, MN



The Hunt for Blue Goo  
*Copper Subsurface Organisms*



Lavatube Microbes on Ferrous Crystals,  
Courtesy of D. Northup

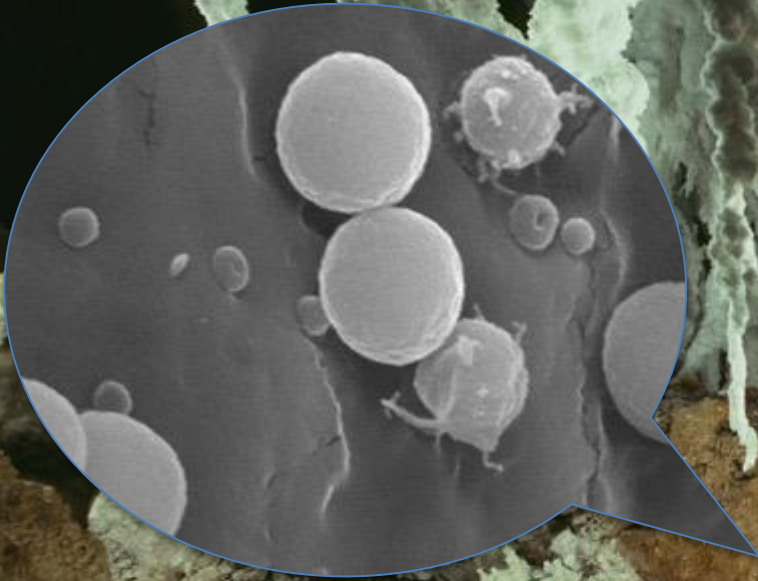




# Subsurface Inventors of New Biochemistry

Stupefying Biodiversity!  
Almost everybody is new to science....

- ✧ Highly partitioned environments
- ✧ Extreme isolation of habitats
- ✧ Limited mobility
- ✧ Inhibition of gene flow
- ✧ Physical limitation of space
- ✧ STRONG evolutionary pressures



e.g. Lechuguilla Cave, NM  
145 miles mapped passages so far  
~ 2X that volume by argon tracer tests  
100s of isolated pools  
Extreme wall heterogeneity  
Widely varying chemistries

Image courtesy of Peter Jones



# Energy Enriched Sulfuric Acid Cave

Cueva de Villa Luz, Tabasco, Mexico

Biodiversity rich!

Biomass rich!

*pH ranges from 9.2 down to 0 !*

Energy:

*Subsurface  $H_2S$*

*Surface-derived organics*



Cave-adapted  
acid tolerant fish!



Biofilm on beetles!



snottites!



microbial biofilms



5 species bats



Photos by Kenneth Ingham,  
Background by Steve Alvarez

Nat Geog 1998, 2000, 2014  
BBC 1999, 2005, 2012, 2013  
NHK 2003, etc.



# Whoa! Is this a photoshop hoax?



Giant Crystal Cave - National Geographic TV Special, Oct 2008  
& National Geographic Magazine, Nov. 2008  
Into the Lost Crystal Cave – National Geographic TV Sequel, Oct. 2010

Image courtesy of Carsten Peters,  
National Geographic Society, © 2008

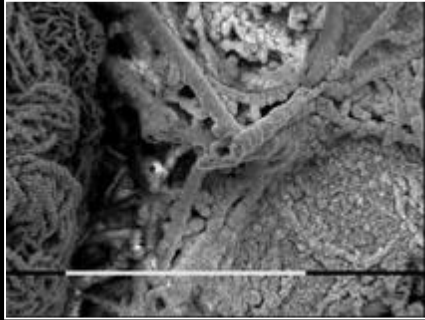
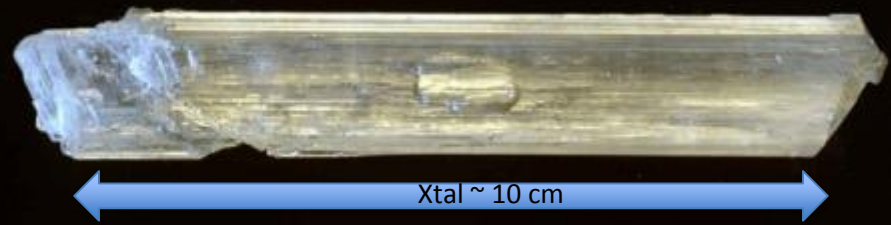


# Naica Mine, Naica Cave System Chihuahua, Mexico

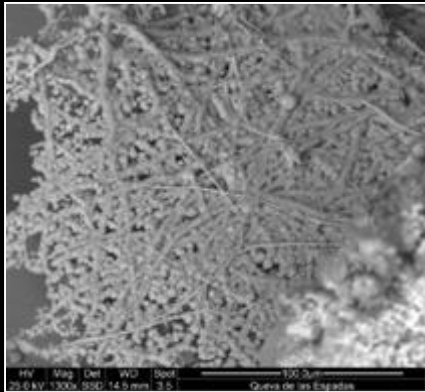


- ❖ Giant selenite crystals  
( $\text{CaSO}_4$  same mineral as wallboard...)
- ❖ 40-60°C (105-140°F, whew!)
- ❖ Water drained for mining
- ❖ Saturated humidity
- ❖ Iron oxide deposits

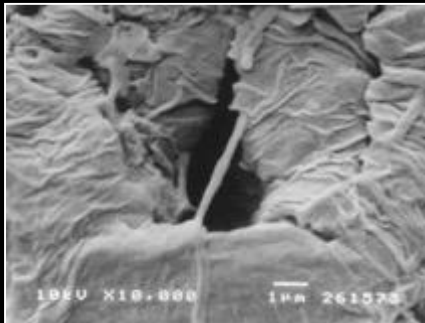
- ❖ Inclusions (holes in the crystals)
- ❖ Solid & fluid
- ❖ Iron and manganese deposits on walls & in inclusions



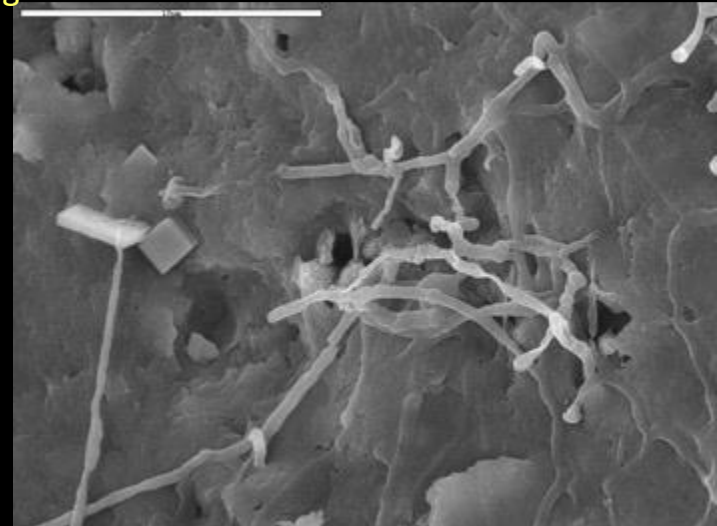
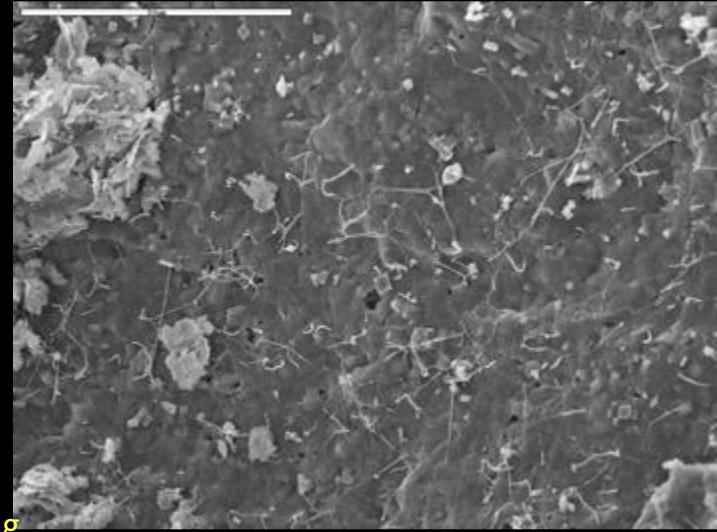
Microbial fossils in inclusions



Live microorganisms encrusting  
clay & iron oxide walls



Micrographs on left,  
courtesy of P. Forti



Micrographs on right  
M. Spilde & P.  
Boston





❖ Results so far....

❖ Xtals ~500, 000+ yrs old  
(Forti et al., Lauritzen et al.)

❖ Sampled inclus. ~10-50, 000 yrs old

❖ DNA directly recovered  
& sequenced, ~ 40+ strains

❖ 65+ live cultures growing!

❖ Many viruses present!  
(Suttle, Chan, Winget at UBC)





# The Hunt for Blue Goo

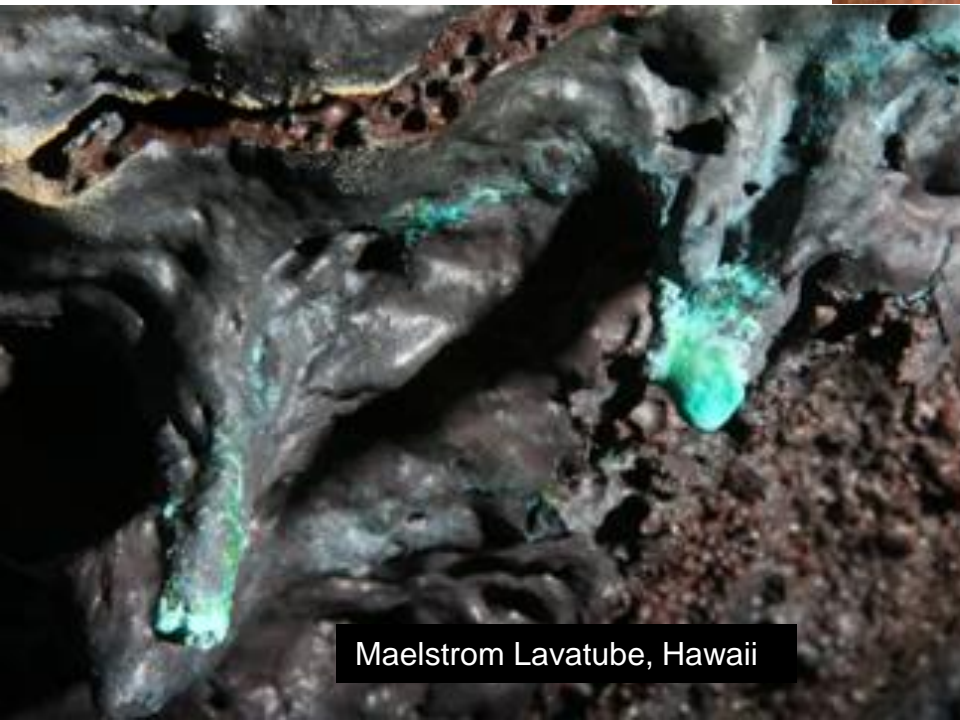
## *Copper Subsurface Organisms*



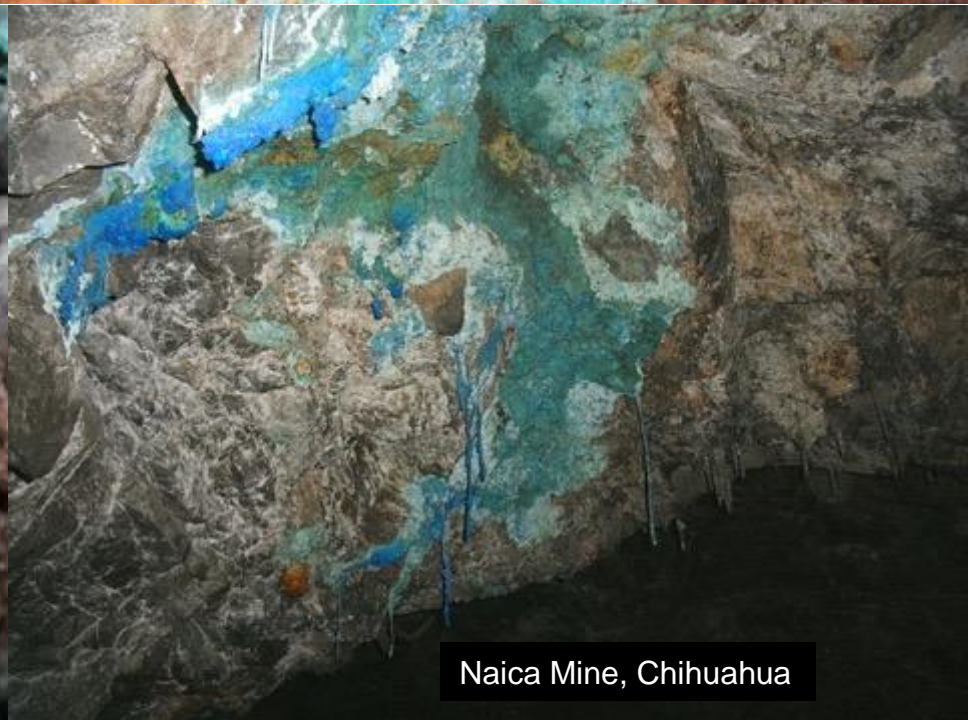
"Diseased" Botallackite  
Harvard Mineral Museum



Malequita Cave,  
Venezuela



Maelstrom Lavatube, Hawaii



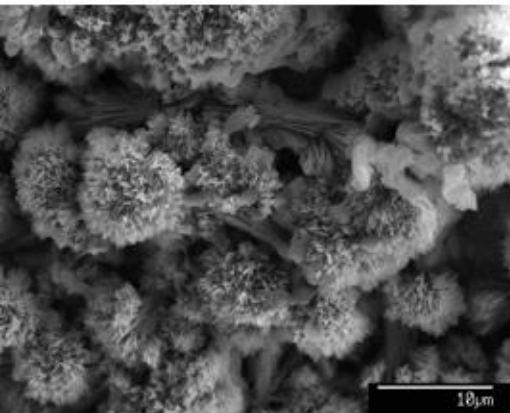
Naica Mine, Chihuahua



30 months after inoculation  
growth is visible

4.5 years significant mineral  
precipitation

Fungal/bacterial consortium  
Copper sulfide oxidizer bacteria  
Elemental copper stored in fungal hyphae  
Copper oxides produced (malachite, azurite)

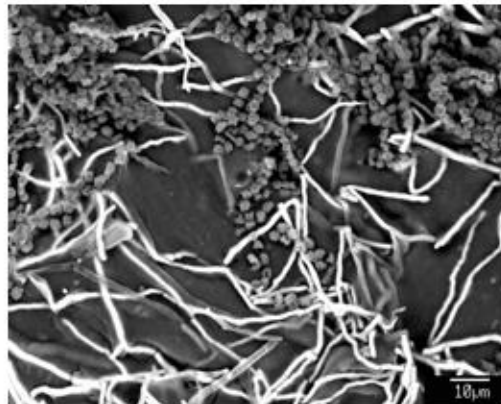


~~Now at 8 yrs...~~

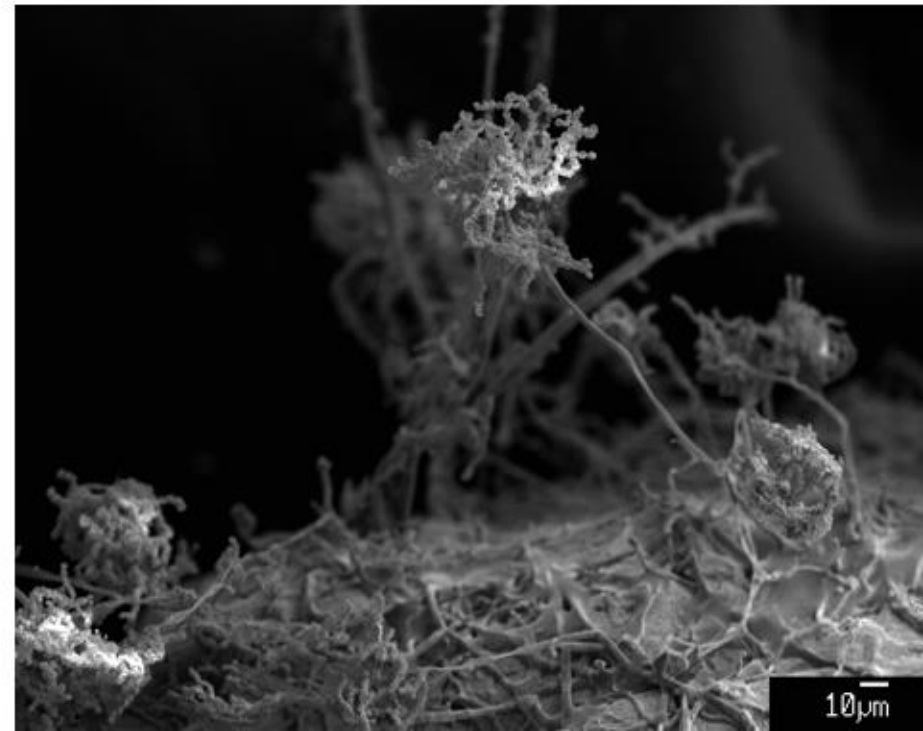
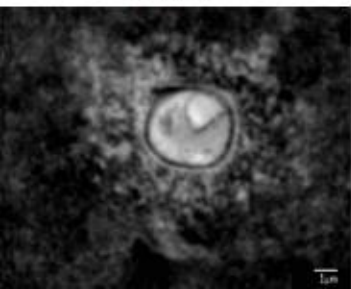
~~Now at 13 yrs!~~

Now at 15 yrs!

SEM backscatter



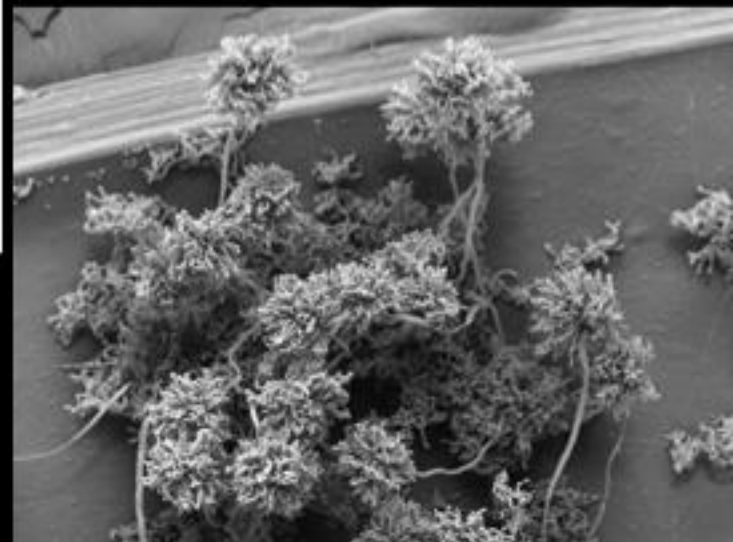
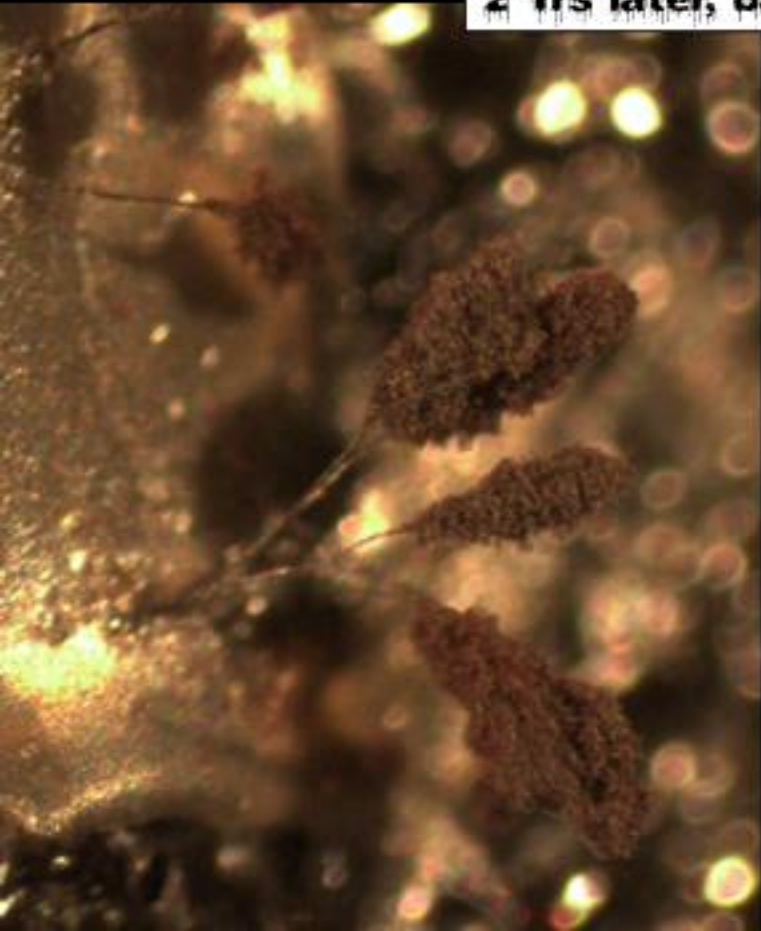
TEM



# The Microbes That Wouldn't DIE!!!!



Air Dried  
Vacuum Dried,  $\sim 100^{\circ}\text{C}$   
Coated in Au/Pd  
Zapped repeatedly w/ electron  
beams in a hard vacuum!!!  
2 Yrs later, back from the dead

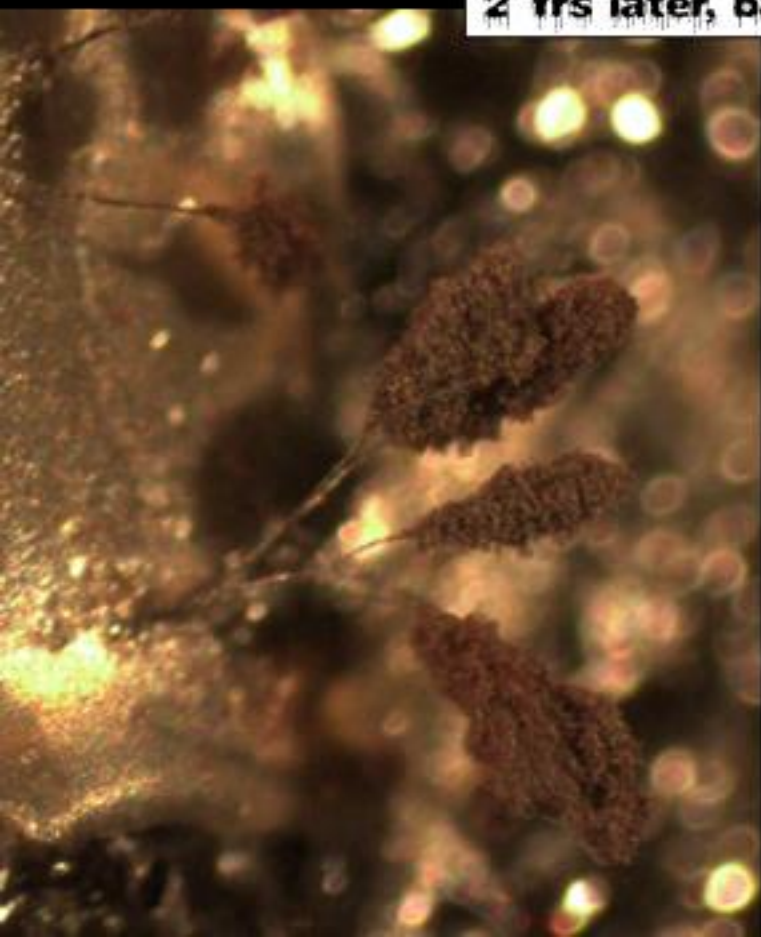




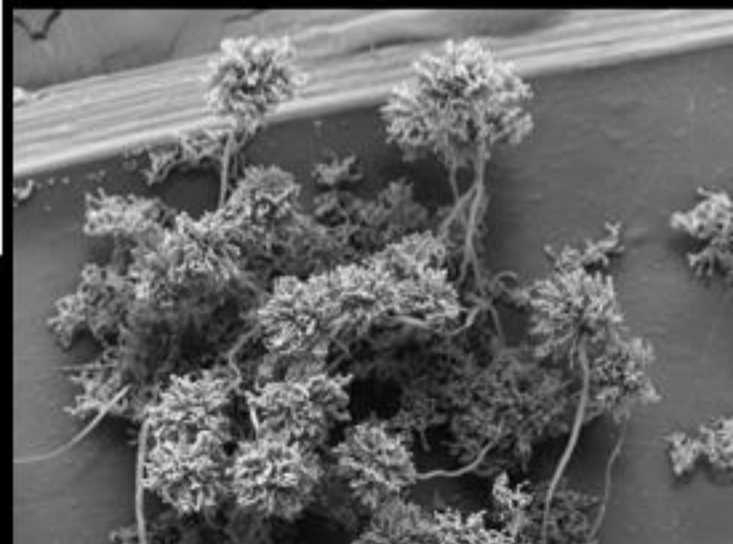
# The Microbes That Wouldn't DIE!!!!



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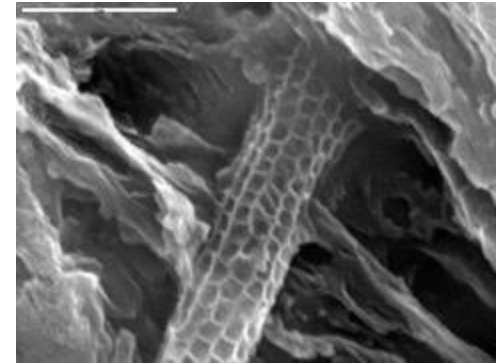
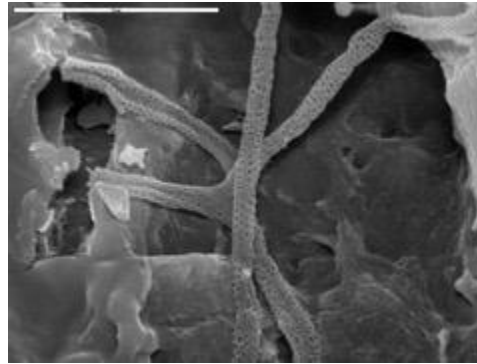
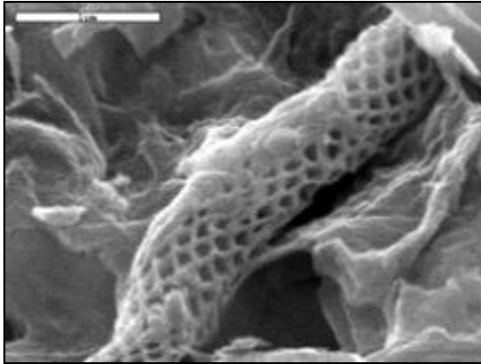
We've now done  
this 4 times!



# In our cave work, we are already dealing with sensitive “alien” biology...

What are these??? Do you know? We don't....

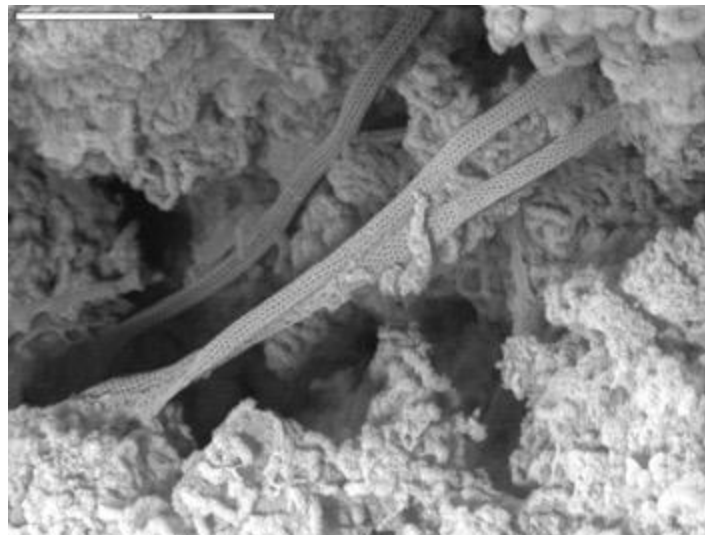
We are finding them in caves all over the world.



Subsurface geomicrobiology is helping us to prepare for the search for life in caves on Earth, on Mars, & icy moons.

What are these, o Wise Omnipotent Professor Boston?

Gosh, Eager Young Student... I haven't the foggiest...



DNA analysis doesn't help us... Too many organisms!



*Exploration presents unparalleled value but also risk.*



Mario Corsalini, Dec. 2009  
NGS expedition to Naica  
*Image by M.N. Spilde*

Lost Dec. 2010 in climbing accident at Hielo Patagonico, Argentina



# Danger Focuses the Mind!

- poisonous atmospheres
- great heat or cold
- unstable rock masses
- gear failure
- you name it

*powers of observation are distilled*

Iceland Cave  
Image by Sky Cohen, *Mind\_Virus*, imgur



*When exploration is coupled with the intellectual discipline of science, understanding happens.*



Aaron Curtis, Warren Ice Cave, Mt. Erebus, Antarctica

*"That's all Folks!"*

© Kenneth Ingham Photography



*Wanna See My Chiggers???*  
Photo courtesy of Kenneth Ingham